First Magnetic Field Detection on a Class I Protostar[1]

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ABSTRACT

Strong stellar magnetic fields are believed to truncate the inner accretion disks around young stars, redirecting the accreting material to the high latitude regions of the stellar surface. In the past few years, observations of strong stellar fields on T Tauri stars with field strengths in general agreement with the predictions of magnetospheric accretion theory have bolstered this picture. Currently, nothing is known about the magnetic field properties of younger, more embedded Class I young stellar objects (YSOs). It is believed that protostars accrete much of

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their final mass during the Class I phase, but the physics governing this process remains poorly understood. Here, we use high resolution near infrared spectra obtained with NIRSPEC on Keck and with Phoenix on Gemini South to measure the magnetic field properties of the Class I protostar WL 17. We find clear signatures of a strong stellar magnetic field. Analysis of this data suggests a surface average field strength of 2.9 ± 0.43 kG on WL 17. We present our field measurements and discuss how they fit with the general model of magnetospheric accretion in young stars.

Subject headings: accretion, accretion disks — stars: pre–main-sequence — stars: individual (WL 17) —

1. Introduction

It is now generally accepted that accretion of circumstellar disk material onto the surface of classical T Tauri stars (CTTSs) is controlled by strong stellar magnetic fields (e.g. see review by Bouvier et al. 2007). CTTSs represent Class II sources in the classification system defined by Lada (1987). The definition is based on a gradually falling spectral energy distribution (SED) beyond $\sim 1\mu$m. This SED shape is believed to arise from a geometrically thin, optically thick accretion disk containing a high concentration of submicron sized dust grains (e.g. Bertout et al. 1988). At some level, the final mass of these forming stars is determined by how much of this disk material accretes onto the central star. Additionally, it is within the disks around these low mass pre-main sequence stars that solar systems similar to our own form. It is critical to understand how the central young star interacts with and disperses its disk in order to understand star, and particularly planet, formation.

The Class I sources defined by Lada (1987) represent one of the earliest stages of star formation and are identified by a rising SED. These sources are deeply embedded within molecular clouds and are very faint or undetectable at optical wavelengths because of a thick envelope of circumstellar dust. It has been commonly thought that Class I objects represent an earlier evolutionary stage relative to Class II sources, with the paradigm emerging that Class I sources are young protostars near the end of their bulk mass accretion phase. This paradigm is bolstered by the very weak photospheric absorption features in near infrared (IR) spectra of these objects (e.g. Casali & Matthews 1992; Greene & Lada 1996, 2000). The lack of absorption lines was interpreted by these authors as the result of strong veiling produced by emission originating in a vigorously accreting circumstellar disk which is being fed by an infalling envelope. This emission is reprocessed by the dusty envelope which results in both the observed featureless continuum and the rising SED. As the accretion rate in the

disk weakens and the thick circumstellar envelope either accretes onto the star plus disk system or is disrupted by strong outflows, it is generally thought that Class I objects evolve into Class II sources.

This general paradigm has been recently challenged by White & Hillenbrand (2004) who find no strong differences in the properties of the central stellar source between a sample of optically selected Class I and Class II sources in Taurus. On the other hand, Doppmann et al. (2005) argue that the White & Hillenbrand (2004) results are biased by their optical selection of these Class I young stellar objects (YSOs). Doppmann et al. (2005) perform an extensive IR study of Class I YSOs in several star forming regions and conclude that, while there is a fair amount of spread in the stellar and accretion properties of these objects, the general paradigm of Class I sources representing an earlier, higher accretion rate phase of stellar evolution relative to Class II sources is borne out (see also Prato et al. 2009).

Some of the confusion and disagreement over the true nature of the Class I YSOs may be due to variability. It has been suggested that the bulk of a star's final mass is accreted through episodic events where the accretion rate through the disk increases by a factor of $10 - 1000$ for some period of time (e.g., Hartmann 1998). These episodes of rapid disk accretion may be what we recognize as FU Orionis events (Hartmann & Kenyon 1996), with these events occuring more frequently during the Class I stage. As a result, Class I objects should display a large range of accretion behavior, with some objects accreting at close to typical CTTS rates, while others are accreting much more rapidly than this. Qualitatively, such a picture matches the range of behavior found in these sources in recent studies (Doppmann et al. 2005, White et al. 2007, Prato et al. 2009).

Since Class I YSOs are often rapidly accreting material, the question arises as to how this process occurs. There is substantial evidence to show that FU Ori outbursts are the result of very rapid disk accretion (for a review see Hartmann & Kenyon 1996). The evidence also suggests that when these objects are not in outburst, accretion onto the central protostar occurs through a disk with infalling material from the envelope piling up in the disk (e.g. Bell 1993). Such a scenario can explain the apparent low luminosity of some Class I sources relative to what is expected if the infalling material from the envelope were to land initially on the central object (Kenyon et al. 1993, 1994). These observations of FU Ori and lower luminosity Class I YSOs suggest that accretion onto the central source occurs primarily through a disk whether a particular YSO is in a high or low accretion state. For the Class II sources (CTTSs) this accretion process appears to be well described by the magnetospheric accretion paradigm (see Bouvier et al. 2007 for a review), but it is currently unclear to what extent this model is appropriate for Class I protostars.

The magnetospheric accretion model is successful at explaining a number of obsverations

of CTTSs. A key question in the study of these stars is to understand how they can accrete large amounts of disk material with high specific angular momentum, yet maintain rotation rates that are observed to be relatively slow (e.g. Hartmann & Stauffer 1989, Edwards et al. 1994). This problem is solved in current magnetospheric accretion models by having the stellar magnetic field truncate the inner disk, typically near the corotation radius, and channel the disk material onto the stellar surface, most often at high stellar latitude. The angular momentum of the accreting material is either transferred back to the disk (e.g., Königl 1991; Cameron & Campbell 1993; Shu et al. 1994) or is carried away by some sort of accretion powered stellar wind (e.g., Matt & Pudritz 2005). Greene and Lada (2002) analyzed the stellar parameters and mass accretion rate of the Class I source Oph IRS 43 and showed that these were consistent with magnetospheric accretion models provided the magnetic field on this source is on a order a kG in strength. Covey et al. (2005) analyzed the rotational properties of Class I sources and found that while they are rotating more rapidly than CTTSs on average, they are not rotating at breakup velocities. These observations could be interpreted in the standard magnetospheric accretion paradigm if the accretion rates of Class I sources are larger on average than those of CTTSs.

Magnetospheric accretion naturally requires a strong stellar magnetic field. Several TTSs have now been observed to have strong surface magnetic fields (Basri et al. 1992; Guenther et al. 1999; Johns–Krull 2007; Johns–Krull et al. 1999b, 2004; Yang et al. 2005, 2008), and strong magnetic fields have been observed in the formation region of the He I emission line at 5876 Å (Johns–Krull et al. 1999a; Valenti & Johns–Krull 2004; Symington et al. 2005; Donati et al. 2007, 2008), which is believed to be produced in a shock near the stellar surface as the disk material impacts the star (Beristain, Edwards, & Kwan 2001). While a considerable amount is now known about the magnetic field properties of Class II YSOs, almost nothing is known directly about the magnetic field properties of Class I sources. While not a Class I source, FU Ori has recently shown evidence for a magnetic field in its disk, revealed through high resolution spectropolarimetry (Donati et al. 2005); however, there are currently no observations of magnetic fields on the surface of a Class I protostar. This is in part due to their faintness and the need for substantial observing time on $8 - 10$ m class telescopes equipped with high resolution near IR spectrometers in order to obtain the necessary data.

In order to begin to address the magnetic field properties of Class I sources, we have begun an observational program to survey the magnetic field properties of several Class I YSOs in the ρ-Ophiuchi star forming region. Here, we report on our first field detection on the Class I source WL 17 (2MASS J16270677-2438149, ISO-Oph 103). This source has a rising IR SED (Wilking et al. 1989) with a spectral index of $\alpha \equiv d\log\lambda F_\lambda/d\log\lambda = 0.61$ over the $2 - 24$ μm region (Evans et al. 2009). WL 17 has been detected in X-rays (Imanishi et

al. 2001; Ozawa et al. 2005) suggesting the star is magnetically active. The temperature (T_{eff}= 3400 K) and luminosity ($L_* = 1.8L_\odot$) of WL 17 (Doppmann et al. 2005) give it a mass of $\sim 0.31M_\odot$ and an age $\sim 10^5$ years using the tracks of Siess et al. (2000). In this paper, we look for Zeeman broadening of K-band Ti I lines in high resolution spectra of WL 17 to diagnose its magnetic field properties. Magnetic broadening is easiest to detect when other sources of line broadening are minimized, and the small rotation velocity of WL 17 ($v\sin i = 12$ km s^{-1}; Doppmann et al. 2005) is a great advantage for this work. Muzerolle et al. (1998) derive an accretion luminosity of $\sim 0.3L_\odot$ based on the Br-γ line luminosity measurements of Greene and Lada (1996). This accretion luminosity implies a mass accretion rate of $\dot{M} \sim 1.5 \times 10^{-7}M_\odot$ yr^{-1} using equation (8) of Gullbring et al. (1998) with the disk truncation radius assumed to be at $5R_*$. While there are reasons to be concerned about this mass accretion rate estimate (which are discussed in §4), such a truncation radius implies a stellar field of about a kilogauss. Detecting and measuring that field is the goal of the current work. In §2 we describe our observations and data reduction. The magnetic field analysis is described in §3. In §4 we give a discussion of our results, and §5 summarizes our findings.

2. Observations and Data Reduction

Spectra analyed here for magnetic fields on WL 17 come from two sources. Keck NIR-SPEC data taken on UT 10 July 2001 is analyzed along with Gemini Phoenix data. The Keck data have already been published by Doppmann et al. (2005) and the reader is referred to that paper for observing and data reduction details. For reference, the resolution of the NIRSPEC data is $R \equiv \lambda/\delta\lambda \equiv 18,000$ (16.7 km s^{-1}). Spectra of WL 17 were acquired on UT 03 April 2006 with the Phoenix near-IR spectrograph (Hinkle et al. 2002) on the 8-m Gemini South telescope on Cerro Pachon, Chile. Spectra were acquired with a 0$\farcs$35 (4-pixel) wide slit, providing spectroscopic resolution $R = 40,000$ (7.5 km s^{-1}). The grating was oriented to observe the spectral range $\lambda = 2.2194$–2.2300 μm in a single long-slit spectral order, and a slit position angle of 90° was used. The seeing was approximately 0$\farcs$50 in K band through light clouds, and WL 17 data were acquired in two pairs of exposures of 1200 s duration each. The telescope was nodded 5$''$ along the slit between integrations so that object spectra were acquired in all exposures for a total of 80 minutes of integration time on WL 17. The B1V star HR 5993 was observed similarly but with shorter exposures for telluric correction of the WL 17 spectra. Both WL 17 and HR 5993 were observed at similar airmasses, $X = 1.01$ - 1.05. Observations of a continuum lamp were acquired for flat fielding.

All data were reduced with IRAF. First, pairs of stellar spectra taken at the two nod

positions were differenced in order to remove bias, dark current, and sky emission. These differenced images were then divided by a normalized flat field. Next, bad pixels were fixed via interpolation with the *cosmicrays* task, and spectra were extracted with the *apall* task. Spectra were wavelength calibrated using low-order fits to 7 telluric absorption lines observed in each spectrum, and spectra at each slit position were co-added. Instrumental and atmospheric features were removed by dividing wavelength-calibrated spectra of WL 17 by spectra of HR 5993 for each of the two slit positions. Final spectra were produced by combining the corrected spectra of both slit positions and then normalizing the resultant spectrum to have a mean continuum flux of 1.0.

3. Analysis

The most successful approach for measuring magnetic fields on late–type stars in general has been to measure Zeeman broadening of spectral lines in unpolarized light (Stokes I e.g., Robinson 1980; Saar 1988; Valenti et al. 1995; Johns–Krull & Valenti 1996; Johns–Krull 2007). In the presence of a magnetic field, a given spectral line will split up into a combination of both π and σ components. The π components are linearly polarized parallel to the magnetic field direction; and the σ components are circularly polarized when viewed along the magnetic field, and linearly polarized perpendicular to the field when viewed from that direction. The exact appearance of a line depends then on the details of the field strength and direction, even when viewed in unpolarized light. For any given Zeeman component (π or σ), the splitting resulting from the magnetic field is

$$\Delta\lambda = \frac{e}{4\pi m_e c^2}\lambda^2 gB = 4.67 \times 10^{-7}\lambda^2 gB \quad \mathrm{m\mathring{A}}, \tag{1}$$

where g is the Landé-g factor of the transition, B is the strength of the magnetic field (given in kG), and λ is the wavelength of the transition (specified in Å).

Class I YSOs are relatively rapid rotators (e.g., Covey et al. 2005) compared to most main sequence stars and most TTSs in which Zeeman broadening has been detected, though WL 17 in particular has a relatively low $v\sin i$. Equation (1) shows the broadening due to the Zeeman effect depends on the second power of the wavelength, whereas Doppler broadening due to rotation or turbulent motions depends on wavelength to the first power. Thus, observations at longer wavelength are generally more sensitive to stellar magnetic fields. There are several Ti I lines in the K band which are excellent probes of magnetic fields in late-type stars (e.g. Saar & Linsky 1985; Johns–Krull 2007), and here we observe 4 of them with NIRSPEC: (air wavelengths) 2.22112 μm with $g_{eff} = 2.08$, 2.22328 μm with $g_{eff} = 1.66$, 2.22740 μm with $g_{eff} = 1.58$, and 2.23106 μm with $g_{eff} = 2.50$. We observe

the first 3 of these with Phoenix. In addition to the strongly Zeeman sensitive Ti I lines, our wavelength settings also record a few additional atomic lines that are weaker and less Zeeman sensitive (lower Landé-g values) as well as the $v = 2 - 0$ CO bandhead at 2.294 μm for the case of the NIRSPEC data. The CO lines are much less magnetically sensitive than the Ti I lines and provide a good check on other line broadening mechanisms.

In order to measure the magnetic field properties of WL 17, we directly model the profiles of several K band photospheric absorption lines. Our spectrum synthesis code and detailed analysis technique for measuring magnetic fields using these K band lines is described elsewhere (Johns–Krull et al. 1999b; Johns–Krull et al. 2004, Yang et al. 2005). Here, we simply review some of the specific details relevant to the analysis presented here. In order to synthesize the stellar spectrum, we must first specify the atmospheric parameters: effective temperature (T_{eff}), gravity (log g), metallicity ([M/H]), microturbulence (v_{mic}), macroturbulence (v_{mac}), and rotational velocity ($v \sin i$). Rotational broadening in YSOs is large compared to the effects of macroturbulence. This makes it difficult to solve for v_{mac} separately, so a fixed value of 2 km s^{-1} is adopted here as it was in the above mentioned papers. Valenti et al. (1998) found that microturbulence and macroturbulence were degenerate in M dwarfs, even with very high quality spectra. Therefore, for the low turbulent velocities considered here, microturbulence is neglected, allowing v_{mac} to be a proxy for all turbulent broadening in the photosphere. While v_{mic} and v_{mac} can in principle have different effects of the spectral lines (v_{mic} potentially affecting the line equivalent width) at the relatively low resolution and signal-to-noise used here, the effect of the two mechanisms on the *shape* of the spectral lines is equivalent, and the corresponding broadening is significantly less than that due to the resolution or magnetic fields. Any errors in the intrinsic line equivalent widths that result from an inaccurate value of v_{mic} can in principle be compensated for by small errors T_{eff}, log g, [M/H], or the derived K band veiling.

With the turbulent broadening specified, estimates are still needed for T_{eff}, log g, $v \sin i$, and [M/H] for WL 17. Doppmann et al. (2005) find $T_{\mathrm{eff}} = 3400$ K and a gravity of log $g = 3.7$ for WL 17. For the stellar atmosphere then, we take the model from a grid of "NextGen" atmospheres (Allard & Hauschildt 1995) which is equal in effective temperature (3400 K) and closest in gravity (log $g = 3.5$) to the values determined for WL 17. Yang et al. (2005), using the 4 Ti I lines covered in the NIRSPEC data here, performed several tests of the magnetic analysis methods used here to see how sensitive the results are to small errors in the effective temperature and gravity assumed in the magnetic analysis. They find that a 200 K error in T_{eff} or 0.5 dex error in log g typically results in less than a 10% error in the derived magnetic field strength. Therefore, we are confident that our particular choice for the stellar atmosphere will not lead to significant error in the magnetic field properties we estimate for WL 17. Finally, solar metallicity is often assumed for young stars, and this assumption is

supported by the few detailed analyses that have been performed (e.g. Padgett 1996). We assume solar metallicity here for WL 17. With the above quantities specified, we can then synthesize spectra for our lines of interest using the polarized radiative code SYNTHMAG (Piskunov 1999).

The rotational broadening of WL 17 has been meaured by Doppmann et al. (2005), where they find $v \sin i = 12$ km s^{-1}. The analysis of Doppmann et al. (2005) used the CO bandhead data used here to measure $v \sin i$. Since the CO lines are very insensitive to magnetic fields, we expect this to be an accurate estimate of the rotational broadening of WL 17; however, we let $v \sin i$ be a free parameter of our fits described below. As mentioned above, Class I sources are often observed to have substantial K band veiling (e.g., Greene & Lada 1996). Veiling is an excess continuum emission which, when added to the stellar spectrum, has the effect of weakening the spectral lines of the star in continuum normalized spectra. Near infrared veiling is assumed to arise from the disk around young stars. Veiling is measured in units of the local stellar continuum, and Doppmann et al. (2005) found a K band veiling of $r_K = 3.9$ for WL 17 using the same NIRSPEC data we use in part here. Doppmann et al. (2003) showed that when magnetic fields are unaccounted for in spectroscopic analysis, the results can be somewhat biased. Therefore, we choose to let the K band veiling be an additional free parameter of the spectral fitting performed here. In addition, we attempt to simultaneously fit both Keck NIRSPEC and Gemini Phoenix data which were observed at different times. CTTSs regularly show significant variations in their K band flux on timescales as short as a day (and occasionally shorter), likely as a result of accretion variability (Skrutskie et al. 1996, Carpenter et al. 2001, Eiroa et al. 2002). Additionally, Barsony et al. (2005) have shown the the near-IR brightness of WL 17 is variable, suggesting the K band veiling of WL 17 may be variable. Therefore, we separately solve for the K band veiling in the Keck and Gemini data.

In previous studies of the magnetic field properties of TTSs it was found that the Zeeman sensitive Ti I lines could not be well fit with a single value of the magnetic field strength. Instead, a distribution of magnetic field strengths provide a better fit (Johns–Krull et al. 1999b, 2004; Yang et al. 2005; Johns-Krull 2007). It was also found that fits to the spectra are degenerate in the derived field values unless the fit is limited to specific values of the magnetic field strength, separated by ~ 2 kG, which is the approximate "magnetic resolution" of the data. While the NIRSPEC data used here are slightly lower in resolution, the Phoenix data are a bit higher in spectral resolution than that used in the studies cited above. Therefore, we use the same limitations when fitting the spectra of WL 17. We assume the star is composed of regions of 0, 2, 4, and 6 kG magentic field, and we solve for the filling factor, f_i, of each of these components subject to the constraint $\Sigma f_i = 1.0$. The different regions are assumed to be well mixed over the surface of the star – different components

are not divided up into well defined spots or other surface features. The field geometry is assumed to be radial in all regions. Another key assumption is that the temperature structure in all the field regions is assumed to be identical for the purpose of spectrum synthesis: the fields are not confined to cool spots or hot plage–like regions. A final assumption we make here is that the photospheric magnetic field properties of the star are the same between the two observing epochs. This may or may not be a good assumption. Substantial variability is seen in CTTSs, both photometrically and spectroscopically, which has been interpreted as rotational modulation of a non axisymmetric stellar magnetosphere (e.g., see Bouvier et al. 2007 for a review). This certainly suggests variation of the field geometry above the star, but not necessarily as much variation of the photospheric field itself. Very little is known about variations over timescales of months to years in the photospheric field properties of CTTSs (and nothing is known regarding Class I sources). Two field measurements exist for BP Tau (Johns–Krull et al. 1999b; Johns–Krull 2007) and for T Tau (Guenther et al. 1999; Johns–Krull 2007), and for both stars, the mean field strengths recovered from the two epochs agree to within the quoted uncertainties. We therefore assume identical field properties between the two epochs for WL 17 and show below that this provides a good match to the data within the uncertainties.

There are then 6 free parameters in our model fits: the K band veiling, r_K, for each observing epoch; the value of f_i for the 2, 4 and 6 kG regions ($\Sigma f_i = 1$, so the filling factor of the 0 kG field region is set once f_i is determined for the other 3 regions); and the value of $v \sin i$. Synthetic spectra are convolved with a Gaussian of the appropriate width to represent the spectral resolution before comparison with the data. We have compared both calibration lamp lines and non-saturated telluric lines to Gaussian fits and find that the line profiles are well matched by this assumed line shape. We are therefore confident that a Gaussian is a good approximation for the instrumental profile. We solve for our 6 free parameters using the nonlinear least squares technique of Marquardt (see Bevington & Robinson 1992) to fit the model spectra to the observed spectra shown in Figure 1. In our first attempt, labelled F1 in Table 1, the entire observed region shown in Figure 1 is used in the fit. The parameters derived from all our fits are listed in Table 1. In Figure 1 we show the spectra of WL 17 in the regions of the Zeeman sensitive Ti I lines and the CO bandhead along with our best fitting model spectrum (F1). Also included in the figure is a model with no magnetic field for comparison. The Zeeman sensitive Ti I lines at 2.2211, 2.2233, and 2.2274 μm (Landé-$g_{eff} = 2.08, 1.66, 1.58$, respectively) are significantly broader in the Phoenix data ($R = 40,000$) than is predicted by the model with no magnetic field. On the other hand, the width of the Zeeman insensitive (Landé-$g_{eff} = 0.50$) Sc I line at 2.2266 μm is accurately predicted by both models due to its much weaker magnetic broadening. This suggests that the excess broadening seen in the Ti I lines is not due to an error in our

assumed instrumental profile. In the lower resolution ($R = 18,000$) NIRSPEC data, the Ti I lines again appear broader than predicted by the model with no magnetic field, though the higher veiling associated with that data makes the lines weaker which combined with the noise in the data makes the reality of the excess broadening less certain than in the Gemini Phoenix data. However, the NIRSPEC data are fully consistent with the magnetic broadening clearly seen in the Phoenix data. The mean field, $\bar{B} = \Sigma B_i \times f_i$, that we find for WL 17 is 2.9 kG.

In the spectral regions used for this analysis there are some relatively strong telluric absorption lines. The spectra shown in Figure 1 have been corrected for telluric absorption; however, the regions affected by this absorption are likely more uncertain than regions not affected by such absorption. In order to test the sensitivity of our results to possible errors in the telluric correction, we increased the uncertainty of spectral regions where the telluric absorption lines went below 97% of the continuum during the fitting process. These regions are shown in the bold lines above the spectra in Figure 1. In these regions, we increased the uncertainty by a factor of 3 and reperformed the fit. The fit parameters derived in this way are also given in Table 1 as those derived from constraints F2. The values of the fitted parameters are almost identical to those derived above (constraints F1). A second concern is that the numerical fitting method might be misled by small changes in χ^2 due to the inclusion of large amounts of continuum regions on which the model has no real effect. Therefore, we performed a third fit (labelled F3 in Table 1) in which we eliminated much of the continuum and focussed down on the lines for fit constraints. The regions of the spectra used for this fit are shown in bold in Figure 1, and the fit parameters are again reported in Table 1. For this fit, we maintained the uncertainty of the telluric affected regions at 3 times their nominal values. Again, the fitted parameters are nearly identical to those determined in fits F1 and F2.

4. Discussion

Our detection of a mean field of $\bar{B} = 2.9$ kG on WL 17 is the first magnetic field measurement on a Class I protostar. Previous studies using K band data of comparable resolution and signal-to-noise level have shown that the field uncertainties are dominated by systematic effects associated with the choice of magnetic model (Johns–Krull et al. 1999b, 2004; Yang et al. 2008) and possible errors in the stellar parameters used to model the star (Yang et al. 2005). Based on these studies, while the formal uncertainty in the mean field determination is quite low, we estimate the true uncertainty in our mean field measurement of be $\sim 10 - 15$ %. Johns–Krull (2007) measured the mean magnetic field on a sample

of 14 CTTSs in the Taurus star forming region, finding field strengths which ranged from 1.1 to 2.9 kG, with a mean of 2.2 kG. Yang et al. (2005, 2008) measured the mean field on a total of 5 stars in the TW Hydrae association (TWA) finding values that range from 2.3 to 3.5 kG with a mean field of 3.0 kG. Yang et al. (2008) find that this difference in mean field strength between the two samples is marginally significant, with the older stars (TWA) having a larger field strength on average. However, Yang et al. (2008) point out that the TWA stars have smaller radii on average due to their older age (~ 10 Myr compared to ~ 2 Myr for Taurus), and that the mean magnetic flux in the TWA stars is actually smaller than that in the Taurus stars. WL 17 has a field strength that is large relative to the Taurus stars studied by Johns–Krull (2007) and it also has a relatively large radius and corresponding high magnetic flux. On the other hand, WL 17 is in many ways similar to DF Tau, which has both a large radius (3.4 $R_\odot$) and a mean field of 2.9 kG, equal to that of WL 17. Observations of a statistically significant sample of Class I sources will be required to see how their magnetic field properties compare as a group to older populations of Class II and III (diskless T Tauri stars) objects.

Our derived $v \sin i = 11.7$ km s^{-1}, with a formal uncertainty of 0.4 km s^{-1}, is consistent with the value of 12 km s^{-1} reported by Doppmann et al. (2005). The veiling we derive for WL 17 is quite different in the two epochs. For the NIRSPEC data, we find $r_K = 6.4 \pm 0.1$. Using the same NIRSPEC data set, Doppmann et al. (2005) quote a veiling value of $r_K = 3.9$, which includes a correction for a systematic effect seen in the best fit synthesis models to observations of MK standards. The measured veiling from Doppmann et al. (2005) without the correction for the systematic effect was $r_K = 4.9$, based on fits to two wavelength regions containing strong lines of Al, Mg, and Na. The CO bandhead was the third wavelength region used in the Doppmann et al. (2005) study, but was only used to derive the $v \sin i$ rotation value. As a result, there are actually no wavelength regions in common between this study and that of Doppmann et al. (2005) for the purpose of determining r_K. We do note that when using only the CO bandhead region of WL 17, Doppmann et al. find a value of $r_K = 7.1$ (Doppmann, private communication), though this region was not actually used in their final veiling determination.

Another difference between this study and that of Doppmann et al. (2005) for the determination of the veiling is the inclusion of magnetic fields. All the atomic lines used in this analysis and that of Doppmann et al. have some Zeeman sensitivity. At the resolution of the NIRSPEC data ($R = 18,000$) and for the strong, broad (e.g. Na I) lines used by Doppmann et al. (2005), magnetic fields primarily increase the equivalent width of the lines compared to models which do not include fields (Doppmann et al. 2003). As a result, the somewhat stronger lines produced by magnetic models must be diluted by more veiling flux than that required for these same (weaker) lines produced by non-magnetic models

in order to match a given set of observed line strengths. The veiling, r_K, inferred from an observed spectrum will thus be larger when derived by comparison to magnetic models and smaller when derived by comparison to non-magnetic models. This is the effect we see when comparing the results here with those of Doppmann et al. (2005). Our veiling estimate of $r_K = 6.4$ from NIRSPEC is a little less than Doppmann et al. find from the CO bandhead alone, but a little larger than the $r_K = 4.9$ they find from their atomic lines, though accounting for magnetic fields would likely bring their $r_K = 4.9$ value up by some amount. We note that we use a single value of r_K to fit both the CO bandhead and the Ti I line region in the NIRSPEC data (lower two panels of Figure 1). Some of the difference in r_K found by Doppmann et al. (2005) in different wavelength regions is likely due to model atmosphere and line data uncertainties (see also a discussion of this in Doppmann et al. 2005). As a result, it is likely that our formal uncertainty of 0.1 on the veiling is too low, so we arbitrarily increase it by a factor of 3 and estimate a veiling for our NIRSPEC data of $r_K = 6.4 \pm 0.3$. We adopt the same uncertainty for our Phoenix data, which is at a comparable signal-to-noise, giving $r_K = 1.1 \pm 0.3$ for this observation time.

Assuming the veiling differences quoted above result in a corresponding change to the K band source brightness, and that only the strength of the veiling continuum changed between these observations (i.e. that the underlying star remained constant), WL 17 should have been a factor of $(1.0 + 6.4 \pm 0.3)/(1.0 + 1.1 \pm 0.3) = 3.5 \pm 0.5$ brighter in the K band at the time of the Keck NIRSPEC observation relative to the Gemini Phoenix observation. Interestingly, if we adopt the K band veiling correction of Doppmann et al. (2005), the individual veilings for each epoch are lowered, but the predicted flux ratio between the two observing epochs remains almost the same (3.4 instead of 3.5).

The K band flux factor variation of 3.5 calculated above corresponds to a variation of 1.36 magnitudes. There are relatively few studies of the near-IR variability of Class I sources; however, the few that exist suggest that while the implied K band variability of WL 17 is large, it may not be too extreme for such a source. Kenyon and Hartmann (1995) plot a histogram of the standard deviation for protostars in their sample that have two or more K band photometric measurements, finding values that reach as high as $\sigma_K \sim 0.8$. In their study, Park and Kenyon (2002) find values of σ_K up to 0.52. Our two veiling meaurements give $\sigma_K = 0.96$, while Barsony et al. (1997) report $\sigma_K = 0.57$ for WL 17 on the basis of 6 different K band photometric measurements. Barsony et al. (2005) tabulate r_K variations for several sources in ρ Oph, and while none show quite as large a variation as we find for WL 17, a few other show large r_K variations with some ranging in value from $1 - 4$. Barsony et al. (2005) also study the mid-IR variability of their sources, finding that WL 17 varies in 12.5 μm flux by a factor of 2.4 which is similar in magnitude to the factor of 3.5 change in the K band brightness found here. Values of $r_K \geq 0.5$ are usually taken to indicate active

accretion from a circumstellar disk, and large variable K band veiling such as that shown by WL 17 and several other sources in ρ Oph is usually taken as evidence that this accretion can be highly time variable (e.g. Barsony et al. 2005). The exact cause of this high degree of variability is not yet clear however.

The veiling analysis and implied K band photometric variations described above assumes the underlying star remains constant; however, it is likely that the star also possesses cool starspots which could contribute some K band variation due to rotational modulation. Veiling is usually attributed to a source producing a featureless continuum. Starspots themselves contribute very weakly to veiling variations since the spectrum of the spots contains many of the lines in present in the non-spotted photosphere. The potential effect of this can be estimated by measuring the veiling of a non-accreting T Tauri star using another non-accreting star as a template. In the optical, this level of veiling is ~ 0.1 (Hartigan et al. 1991) and should be smaller in the K band since the spot quiet atmosphere contrast is much weaker. Weakly or non-accreting T Tauri stars do show K band brightness variations with a peak-to-peak amplitude ≤ 0.2 magnitudes as a result of spots (e.g. Skrutskie et al. 1996, Carpenter et al. 2001) which is substantially less than the K band variations implied by our veiling measurements or observed by Barsony et al. (2005). Thus, the majority of the K band veiling variation here must be due to changes in the accretion properties of WL 17.

One of the motivations for this study is to see to what extent the magnetospheric accretion paradigm in place for Class II YSOs may be applicable to Class I sources. Johns–Krull et al. (1999b) give equations for predicting the stellar magnetic field strength required for 3 different prescriptions (Königl 1991, Cameron & Campbell 1993, Shu et al. 1994) of magnetospheric accretion theory. The work of Königl (1991) and Shu et al. (1994, see also Camenzind et al. 1990) give the same scaling with stellar and accretion parameters: $B_* \propto M_*^{5/6} R_*^{-3} P_{rot}^{7/6} \dot{M}^{1/2}$. The scaling from Cameron and Campbell (1993) is very similar: $B_* \propto M_*^{2/3} R_*^{-3} P_{rot}^{29/24} \dot{M}^{23/40}$. Using these equations to predict the field on WL 17 is uncertain due to difficulties with estimating the luminosity of WL 17 (which affects the derived mass, radius, and accretion rate). Luminosity estimates for WL 17 range from 1.8 $L_\odot$ (Doppmann et al. 2005) to 0.12 $L_\odot$ (Bontemps et al. 2001). Additional uncertainties also affect the mass accretion rate, and the rotation period of WL 17 is unknown. Assuming $T_{\rm eff} = 3400$ K from Doppmann et al. (2005) is a fairly robust estimate, we use this in combination with the two quoted stellar luminosities to derive the quantities needed to predict the stellar field strength from magnetospheric accretion theory. These stellar properties are reported in Table 2 along with the field predictions for the studies mentioned above. We note that the stellar luminosity from Bontemps et al. (2001) in combination with the 3400 K effective temperature would give WL 17 an age of ~ 5 Myr using the pre-main sequence tracks of

Siess et al. (2000). Such an age would be unusual for a Class I source. The Doppmann et al. (2005) stellar luminosity may be more accurate than the Bontemps et al. (2001) value. This is because the former was derived by using photometric measurements to estimate and correct for the extinction and veiling seen toward the photosphere of the spectroscopically determined effective temperature, while the latter was determined by de-reddening near-IR photometry of WL 17 to intrinsic CTTS colors and assuming an intrinsic J band flux to stellar luminosity relationship for a typical CTTS. The Doppmann et al. (2005) approach corrects for the veiling and effective temperature measured specifically for WL 17, while the Bontemps et al. (2001) technique does not. Nevertheless, we report magnetospheric accretion estimates based on both values of the stellar luminosity in order to illustrate the sensitivity of the expected fields to various stellar parameters, notably the luminosity.

In addition to issues related to the correct luminosity for WL 17, there is additional uncertainty regarding the accretion rate estimate. The value of $\dot{M} \sim 1.5 \times 10^{-7} M_\odot$ yr^{-1} quoted in §1 is based on the accretion luminosity estimate of Muzerolle et al. (1998) which is in turn based on the Br-γ line luminosity estimate from Greene and Lada (1996). A major concern in this process is the extinction correction used to recover the Br-γ line luminosity. For example, Greene and Lada (1996) corrected their data for WL 17 back to the CTTS locus in the JHK color–color diagram, not necessarily back to the stellar photosphere. As an example of the sensitivity to the details of extinction corrections and the photometric data used, we note that Doppmann et al. (2005) also compute Br-γ line luminosities (their Figure 11). These authors de-redden the H-K color to an intrinsic value of 0.6 and then add in a correction for scattered light based on the models of Whitney et al. (1997). This results in a Br-γ line luminosity of $6.8 \times 10^{-4} L_\odot$ (Doppmann, private communication), which in turn gives an accretion luminosity of 2.7 $L_\odot$ using the Muzerolle et al. (1998) relationship. Calculating the mass accretion rate as given in the introduction results is a value of $\dot{M} \sim 1.4 \times 10^{-6} M_\odot$ yr^{-1}. We include the field estimates resulting from this accretion rate in Table 2, and we note that such an accretion rate is about the level needed to accrete a 0.5 $M_\odot$ star in a $\sim 3.5 \times 10^5$ yr. This large accretion rate estimate for a Class I source is also supported by the estimate of $\dot{M} = 1 \times 10^{-6} M_\odot$ yr^{-1} found by Greene and Lada (2002) for Oph IRS 43.

Obviously, the accretion rate and implied magnetic field are fairly sensitive to the details of the Br-γ line luminosity calculation. We therefore recomputed the Br-γ line luminosity from the measured equivalent width value of 4.3 Å (Doppmann et al. 2005), the 2MASS photometry (Skrutskie et al. 2006), and correcting for extinction by de-reddening the JHK colors to the CTTS locus and correcting for an extra $A_K = 0.88$ mag (see Doppmann et al. §3.8). We also used a distance of 135 pc to the ρ Oph cloud (Mamajek 2008). This produced a Br-γ line luminosity of $2.9 \times 10^{-4} L_\odot$, about 2.5 times higher than that given by Greene &

Lada due mostly to the more recent photometry and extinction correction technique. This new line luminosity indicates an accretion luminosity of 0.9 $L_\odot$ from the Muzerolle et al. (1998) relationship, which implies a mass accretion rate of $4.5 \times 10^{-7} M_\odot$ yr^{-1}, which is well bounded by the accretion rates given in Table 2.

All of the above discussion implicitly assumes the Muzerolle et al. (1998) Br-γ accretion luminosity relationship holds for Class I sources; however, this relationship was derived based on a sample of Class II objects. If there are any systematic differences between these and Class I sources, the resulting accretion rate will be in error. For example, if the Br-γ line is more optically thick in Class I sources due to systematically higher accretion rates, the accretion rate we derive above for WL 17 will be lower than the true value. This suggests that the derived accretion rates for WL 17 may be too low.

The rotation period reported in Table 2 is an upper limit based on the stellar radius and measured $v \sin i$. If the rotation period is actually shorter, the derived magnetic field values will be smaller. In this sense, the values reported in the Table are an upper limit depending on the inclination of the source. The field strengths reported in Table 2 are those corresponding to the equatorial field strength for an assumed dipolar field geometry. The polar field strength in such a geometry is twice this value. The mean field of 2.9 kG found for WL 17 is well above the predicted values for the larger luminosity found by Doppmann et al. (2005); while for the lower luminosity of Bontemps et al. (2001), the measured field value may not be strong enough, particularly if the field is not dominated by the dipole component. In most TTSs, the dipole component is found to be weak (Johns–Krull et al. 1999a; Daou et al. 2006; Yang et al. 2007; Donati et al. 2007). It is important to note that the data presented here only probe the photospheric field strength, while providing few constraints on the field geometry. High spectral resolution near-IR circular spectropolarimetry will likely be required to explore the field geometry on Class I YSOs such as WL 17.

In summary, the magnetic field we measure on WL 17 is roughly consistent with predicted magnetic field strength required for magnetospheric accretion. However, detailed quantitative comparisons are greatly hampered due to a number of uncertainties related to other relevant stellar parameters that are currently difficult to estimate for Class I sources (see also the discussion in Prato et al. 2009). Class I sources by their nature are deeply embedded and therefore suffer substantial extinction. Uncertainties involved with the proper way to de-redden observations of these sources, combined with variable accretion luminosity (continuum and line), a general lack of measured rotation periods for Class I objects, and uncertainties in the methods used to measure accretion rates suggest that much work is still left to do before the magnetospheric accretion paradigm can be firmly established or refuted for Class I sources.

On the Sun and active stars, it is expected that magnetic flux tubes are confined at photospheric levels by the gas pressure in the external non-magnetic atmosphere. For example, Spruit & Zweibel (1979) computed flux tube equilibrium models, showing that the magnetic field strength is expected to scale with gas pressure in the surrounding non-magnetic photosphere. Similar results were found by Rajaguru et al. (2002). Field strengths set by such pressure equipartition considerations appear to be observed in active G and K dwarfs (e.g. Saar 1990, 1994, 1996) and possibly in M dwarfs (e.g. Johns–Krull & Valenti 1996). Class I YSOs have relatively low surface gravities and hence low photospheric gas pressures, so that equipartition flux tubes would have relatively low magnetic field strengths compared to cool dwarfs. The maximum field strength allowed for a confined magnetic flux tube is $B_{eq} = (8\pi P_g)^{1/2}$ where P_g is the gas pressure at the observed level in the stellar atmosphere. Here, we take as a lower limit in the atmosphere (upper limit in pressure) the level where the local temperature is equal to the effective temperature (3400 K) in the NextGen models of the appropriate gravity. This is the approximate level at which the continuum forms, with the Ti I lines forming over a range of atmospheric layers above this level at lower pressure. The values of B_{eq} are given in Table 2. The mean field we measure for WL 17 is well above the value of B_{eq} for either assumed luminosity and resulting gravity. This suggests that pressure equipartition does not hold in the case of Class I YSOs, and it also suggests the gas pressure in the atmospheres of these young stars is dominated by their magnetic fields. Indeed, our fit for the magnetic field of WL 17 has only 3% of the surface as field free; however, the uncertainty on the filling factor of this component is such that this is not a significant measurement. It may well be that the entire surface of WL 17 is covered with strong magnetic fields. What is certain is that the field we measure is too strong to be accounted for by current models of dynamo action on fully convective stars, where the field strength is equal to the equipartition value (Bercik et al. 2005, Chabrier & Küker 2006, Dobler et al. 2006) and the filling factor of this field is typically very low (Cattaneo 1999, Bercik et al. 2005). Rapid rotation can enhance field production and may help organize magnetic fields into large scale dipolar or quadrapolar geometries (e.g. Dobler et al. 2006, Brown et al. 2007); however, it is not yet clear that such models can produce mean fields on young stars in the range of $2-3$ kG.

Stellar magnetic fields give rise to "activity" in late-type stars. Activity is typically traced by line emission or broad band emission at high energy wavelengths such as X-rays. Pevtsov et al. (2003) find an excellent correlation between the X-ray luminosity, L_X, and magnetic flux in solar active regions and dwarf type stars with each of these two quantities ranging over almost 11 orders of magnitude. Using the X-ray luminosity–magnetic flux relationship of Pevtsov et al. (2003) with our mean magnetic field measurement of 2.9 kG for WL 17, we can predict L_X for this YSO if the radius is known. In Table 2 we report

the predicted X-ray luminosity values for the two stellar radii implied by the different stellar luminosity estimates of Bontemps et al. (2001) and Doppmann et al. (2005). WL 17 has been detected in X-rays by Chandra (Imanishi et al. 2001) and by XMM (Ozawa et al. 2005), and possibly by ASCA, though crowding was an issue for this latter observation (Kamata et al. 1997). The Chandra observation gives an X-ray luminosity of $L_X = 3.1 \times 10^{29}$ erg s^{-1} while the XMM observation found $L_X = 9.6 \times 10^{29}$ erg s^{-1}. Both values are lower than either of the predicted values in Table 2, though the XMM value of Ozawa et al. (2005) is not much lower than the lower estimate which is based on the Bontemps et al. (2001) luminosity for WL 17. We do note though that the Pevtsov et al. (2003) X-ray luminosity–magnetic flux relationship is based on observed X-ray emission outside obvious flares: the so-called quiescent emission level. The XMM X-ray lightcurve of WL 17 presented by Ozawa et al. (2005) is dominated by a strong, long lasting flare. Thus, the quiescent X-ray emission of WL 17 is likely significantly weaker than the predicted X-ray emission, independent of the exact value of the the stellar radius for WL 17. Pevtsov et al. (2003) found evidence that TTSs were underluminous in X-rays relative to the relationship defined by dwarf stars, and this result appears to hold for a majority of these stars (Johns–Krull 2007; Yang et al. 2008). In that sense, WL 17 follows the same pattern seen in most Class II sources. Johns–Krull (2007) suggested that this might be due to the fact that the magnetic pressure at the surface of these stars is so strong. Perhaps the ubiquitous, strong fields of these young stars inhibit (relative to dwarf stars) photospheric gas motions from moving flux tubes around and building up magnetic stresses which eventually results in coronal heating. Alternatively, WL 17 is deeply embedded and may suffer substantial X-ray attenuation, though this in nominally accounted for in the X-ray measurements.

5.   Summary

We have measured the magnetic field on the Class I source WL 17, and we find the star is largely covered by strong magnetic fields. The surface averaged mean field on the star is 2.9 ± 0.43 kG. Comparing this field with predictions from magnetospheric accretion theory or with X-ray measurements depends fairly sensitively on the value of the stellar radius appropriate for WL 17. For the relatively large luminosity and associated stellar radius from Doppmann et al. (2005), the measured field values are more than strong enough to be consistent with magnetospheric accretion; however, for the lower radius implied by the Bontemps et al. (2001) luminosity, the field may in fact be too weak. For either radius, the measured fields are stronger than expected by pressure balance arguments for magnetic flux tubes confined by a non-magnetic atmosphere, suggesting that the star is likely fully covered by fields. In addition, independent of the radius assumed, the measured X-ray emission is

lower than is to be expected based on correlations established between these two quantities on the Sun and late-type dwarf stars.

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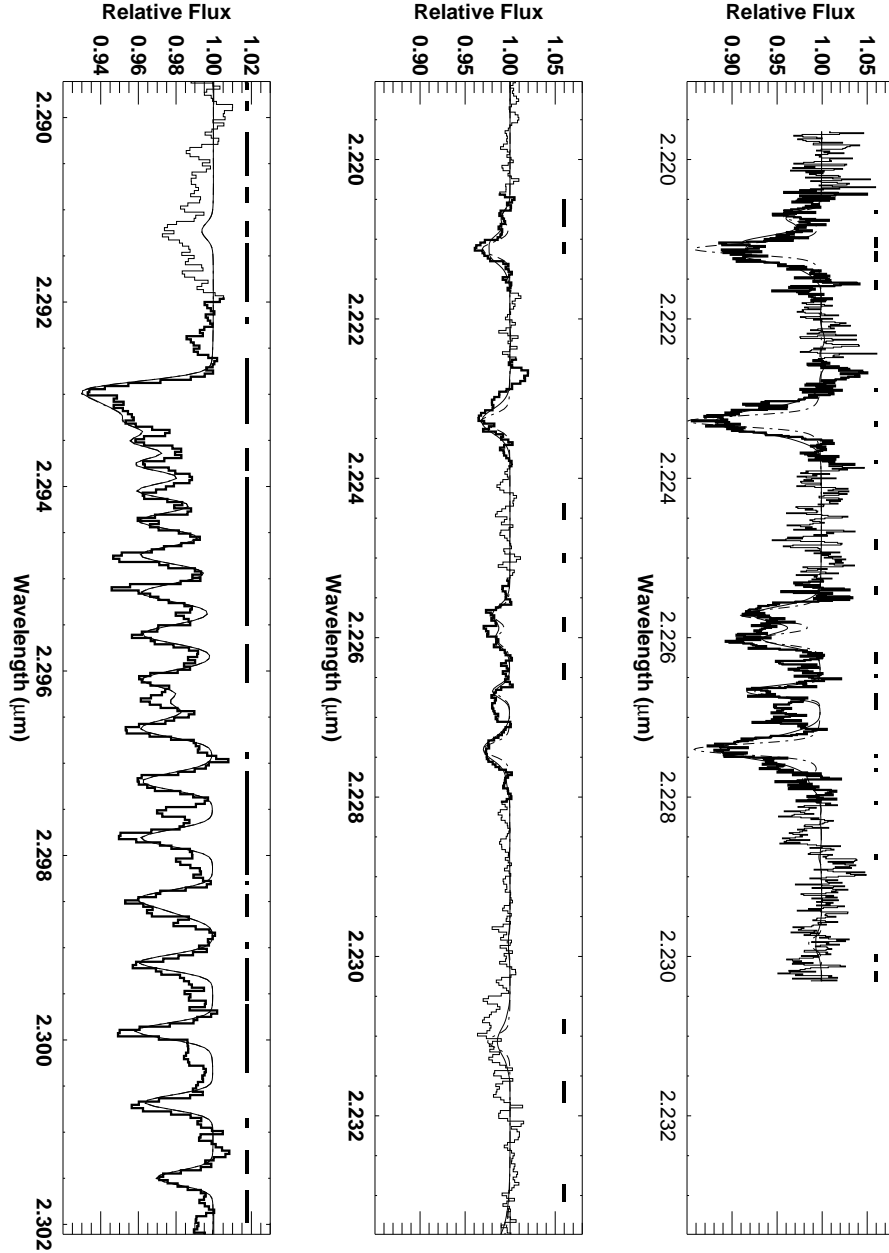Yang, H., Johns–Krull, C. M., & Valenti, J. A. 2008, AJ, in press

Fig. 1.— Fits to the K band spectra of WL 17. The observed spectra are shown as the histogram in each panel. The upper panel shows the Gemini Phoenix data and the bottom two panels show the Keck NIRSPEC spectra. Regions where telluric absorption reached below 97% of the continuum are indicated by the thick lines above the spectra. The bold histogram regions show the parts of the spectra used in the third set of fits (F3) discussed in the text. In each panel, the fits including a magnetic field (from fit F1) are shown in the smooth solid curve, and the best fit with no magnetic field is shown as the dash-dot curve. The upper two panels are plotted on the same scale in both axes to emphasize the change in K-band veiling between the two observing epochs.

Table 1. Fit Parameters

Fit	$v\sin i$ (km s^{-1})	r_K (NIRSPEC)	r_K (Phoenix)	f_{0kG}	f_{2kG}	f_{4kG}	f_{6kG}	$\Sigma B_i \times f_i$ (kG)
F1	11.7	6.4	1.1	0.03	0.60	0.23	0.14	2.9
F2	12.0	6.4	1.0	0.08	0.55	0.21	0.16	2.9
F3	11.7	6.5	1.0	0.03	0.64	0.17	0.16	2.9

Table 2.   Magnetospheric Accretion Predictions

$T_{\rm eff}$ (K)	L_* ($L_\odot$)	R_*[a] ($R_\odot$)	M_*[b] ($M_\odot$)	P_{rot}[c] (days)	$\dot{M}$[d] ($M_\odot yr^{-1}$)	B[e] (kG)	B[f] (kG)	B[g] (kG)	$\log g$ (cgs)	B_{eq} (kG)	L_X[h] (10^{30} erg s^{-1})
3400	1.8	3.9	0.31	16.9	1.5×10^{-7}	0.72	0.33	0.85	2.7	1.06[i]	29.0
3400	0.12	1.0	0.29	4.33	4.3×10^{-8}	4.43	1.74	5.22	3.9	1.44[j]	1.3
3400	1.8	3.9	0.31	16.9	1.4×10^{-6}	2.20	1.18	2.60	2.7	1.06[k]	29.0

[a]Determined from L_* and $T_{\rm eff}$.

[b]Determined from L_* and $T_{\rm eff}$ using Siess et al. (2000) evolutionary tracks.

[c]Upper limit on P_{rot} determined from stellar radius and measured $v \sin i$.

[d]Using Br-γ line luminosity with Muzerolle et al. (1998) relationship to determine L_{acc} which is used with equation (8) of Gullbring et al. (1998) assuming the disk truncation radius is equal to $5R_*$ to find $\dot{M}$.

[e]Equatorial field strength for an assumed dipole using magnetospheric accretion model of Königl (1991).

[f]Equatorial field strength for an assumed dipole using magnetospheric accretion model of Cameron & Campbell (1993).

[g]Equatorial field strength for an assumed dipole using magnetospheric accretion model of Shu et al. (1994).

[h]Predicted X-ray luminosity based on the Pevtsov et al. (2003) relationship between L_X and magnetic flux.

[i]Computed with the NextGen model with $\log g = 3.5$ which is the closest in the grid to the predicted gravity.

[j]Computed with the NextGen model with $\log g = 4.0$ which is the closest in the grid to the predicted gravity.

[k]Same entries as line 1 except for a higher mass accretion rate more typical of Class I sources.